



Digital Transformation and the Working Environment: International Evidence on Safety and Training in Industry 4.0.

Sonia GARCÍA-MORENO¹

¹ University of Castilla-La Mancha (UCLM), 02071, Albacete, Spain;  ORCID No. [0000-0001-7552-5280](https://orcid.org/0000-0001-7552-5280); (corresponding author); sonia.garcia10@alu.uclm.es

Víctor-Raúl LÓPEZ-RUIZ²

² University of Castilla-La Mancha (UCLM), 02071, Albacete, Spain;  ORCID No. [0000-0002-2850-1662](https://orcid.org/0000-0002-2850-1662); Victor.Lopez@uclm.es

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Abstract: Improving the working environment is a structural dimension of Industry 4.0., where technological change affects occupational safety and continuous training. This paper examines whether Industry 4.0. transformation is associated with more robust labor conditions in the European Union and in Germany, Spain, and Romania. The analysis distinguishes between total economic activity and manufacturing to capture differences by sector in safety and workforce adaptation. The study uses harmonized Eurostat data covering different time spans according to the indicator and combines standard measures with derived indicators constructed by the authors. These include accident incidence, severity composition, relative manufacturing differentials and training dynamics. The results show a general decline in accident incidence but also reveal uneven trajectories in the qualitative structure of occupational risk and in the development of training capacity. Germany presents the most stable trajectory, with declining accident incidence, contained severity indicators and an established training structure in firms. Spain shows a more ambivalent pattern. Adult learning improves markedly, but manufacturing remains the clearest safety concern because incidence and severity gaps persist. Romania records rapid gains in adult learning and low accident incidence, although these coexist with a heavier severity burden and a weaker training base in enterprises. The paper does not reject the view that Industry 4.0. can improve safety and training. Rather, it shows that improvement remains partial and uneven when the analysis also considers accident severity and training provided by enterprises. Occupational safety and training, therefore, constitute core conditions for a balanced, resilient, and sustainable industrial transition.

Keywords: Industry 4.0.; working environment; occupational safety; training systems; digital transformation; comparative analysis.

Introduction

Industry 4.0., understood as a structured paradigm of industrial transformation based on the integration of digital, physical, and organizational systems, has usually attracted attention because of its potential effects on productivity, efficiency, and technological upgrading at firm and sectoral levels (Lasi et al., 2014; Brynjolfsson & McAfee, 2014). This perspective is essential, but it remains incomplete when it leaves the working environment outside the core analysis of industrial change. Technological progress reshapes organizational structures, risk profiles, and labor interactions, influencing how work takes place and how firms generate and manage risks (Acemoglu & Restrepo, 2020; Autor, 2015).

From a knowledge management perspective, these changes go beyond the adoption of innovative technologies. They also involve the way organizations create, transfer, and apply knowledge in increasingly complex production environments. Industry 4.0.

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intensifies the circulation of technical, organizational, and preventive knowledge, as workers and firms must interpret data, codify procedures, adapt routines, and learn from operational experience. This is particularly relevant for the two dimensions examined in this paper. Occupational safety depends on the capacity to transform risk information into shared preventive practices, while continuous training reflects the mechanisms through which firms update skills and convert technological change into usable organizational knowledge. In this sense, safety and training are not only labor outcomes. They are also expressions of knowledge dynamics within industrial systems.

Assessing the sustainability of Industry 4.0. requires more than attention to output or operational efficiency. A more complete evaluation must consider the conditions under which technological transformation unfolds, particularly where production systems make more intensive use of data and become more interconnected and organizationally complex. In such contexts, the quality of the working environment becomes a relevant dimension of industrial performance rather than a secondary outcome of technological change.

Among the different elements that shape the working environment, occupational safety and continuous training are especially significant. Safety reflects whether technological and organizational changes lead to more secure and controllable production processes. Training, in turn, conditions the capacity of workers and firms to adapt to new tasks, tools, and requirements for decision making associated with digital transformation. Taken together, these two dimensions offer a useful entry point for assessing whether Industry 4.0. is associated with more robust and sustainable forms of industrial development.

Despite growing interest in the social and organizational implications of digital transformation, empirical evidence jointly examining occupational safety and training within the context of Industry 4.0. remains limited, particularly from a comparative European perspective. Much of the existing literature has focused either on productivity and innovation outcomes or on broader labor market changes, without fully integrating the dimensions of technological change that operate within the workplace (Goos et al., 2014; Acemoglu & Restrepo, 2020). This gap is especially relevant in manufacturing, where technological intensity and exposure to occupational risks are particularly pronounced.

This paper addresses this gap by analyzing the evolution of occupational safety and training as key dimensions of the working environment in the context of Industry 4.0. The analysis adopts a comparative perspective focused on the European Union and three national cases, Germany, Spain and Romania. These countries reflect different industrial structures, technological trajectories and labor market conditions, allowing the identification of both convergent patterns and persistent structural differences. The empirical approach is based on European statistics and distinguishes between total economic activity and manufacturing to capture dynamics that are specific to each sector and associated with technological transformation. By examining trends in accident incidence, severity and participation in education and training, the paper provides a structured assessment of how the working environment evolves alongside digital change. It argues that improvements in safety and training should be understood as structural components of Industry 4.0. rather than as secondary outcomes, and that their joint analysis offers a more complete view of the quality and sustainability of industrial transformation.

The paper is organized as follows. The next section reviews the literature linking Industry 4.0., knowledge management, occupational safety and training. The methodology section describes the data sources, indicators and comparative approach used in the empirical analysis. The results and discussion section examines safety trends, severity patterns, training dynamics and the comparative trajectories of Germany, Spain and Romania. The concluding section summarizes the main findings and discusses their implications for the

assessment of Industry 4.0. as an industrial transition focused on people and grounded in knowledge management.

Literature review.

The literature on industrial transformation has long shown that technological investment alone does not guarantee sustained improvements in firm performance. Early contributions on high-performance work systems argued that firms combining technological change with organizational redesign, clearer task structures, employee involvement and continuous training tend to achieve better results than those relying on capital upgrading in isolation (Appelbaum et al., 2000; Ichniowski et al., 1997;). From this perspective, the working environment is not external to production performance but embedded within it. A safer, more stable and better organized workplace may reduce disruption, support learning processes and contribute to more resilient operational outcomes.

This argument is particularly relevant in the context of Industry 4.0., where digital transformation modifies both the technical and organizational architecture of production. The introduction of automation, data analytics, connected systems and cyber-physical integration may reduce exposure to certain routine risks and improve process control. However, these effects are not automatic. Technological change may also generate new forms of complexity, intensification and cognitive demand if it is not accompanied by appropriate organizational adaptation and clear governance of work processes (Brynjolfsson & Hitt, 2000; Bloom et al., 2012). The relationship between Industry 4.0. and the quality of the working environment should therefore be understood as conditional rather than linear.

Within this broader discussion, occupational safety occupies a central position. Safety outcomes reflect not only the technological characteristics of production systems but also the quality of work organization, risk prevention and managerial coordination. The literature on job design and psychosocial work environments has shown that performance and well-being depend heavily on how demands, control and support are configured within the workplace (Karasek & Theorell, 1990). In parallel, more recent research on safety management has stressed that increasingly complex production environments require more adaptive and integrated approaches to risk control, particularly where advanced technologies alter routines, interfaces and decision structures (Hollnagel, 2014; Badri et al., 2018). In this sense, digital upgrading does not automatically improve safety. Safety depends on how technology is embedded in organizational practice.

Ergonomics and human-centered design further reinforce this interpretation. Research has shown that aligning workplace design, tools and interfaces with human capabilities contributes not only to better health and safety outcomes but also to quality, process stability and organizational learning (Bratianu & Anagnoste, 2011; Bratianu et al., 2011; Dul & Neumann, 2009; Kadir & Broberg, 2021). Similarly, the literature on safety climate has highlighted that the preventive performance of organizations depends on shared perceptions, managerial commitment and the practical integration of safety into everyday work (Zohar, 1980). These contributions are especially relevant for Industry 4.0., where technological sophistication increases the importance of coordination, interpretative capacity and the management of hybrid human machine environments.

Training constitutes the second major pillar of this framework. The literature on skill-biased technological change has consistently shown that digitalization raises the demand for higher-order skills while reducing the relative importance of routine tasks (Autor et al., 2003; Acemoglu & Autor, 2011). In industrial contexts, this implies that the capacity to benefit from digital technologies depends not only on the acquisition of equipment and systems but also on the ability of workers to interpret data, interact with digital tools and adapt to reconfigured production processes. Continuous training, therefore, becomes a

central mechanism through which firms translate technological investment into effective organizational capability (OECD, 2019; World Economic Forum, 2020). Recent European policy approaches increasingly reflect this broader understanding of industrial transformation. Human-centered, sustainable and resilient industry is now framed as a strategic objective, implying that technological progress should be assessed alongside working conditions, learning capacity and wider social outcomes (European Commission, 2021; Eurofound, 2021). Nevertheless, the empirical literature still offers limited comparative evidence integrating occupational safety and training within a common analytical framework. This is particularly visible in cross-country analyses of manufacturing, where the organizational and labor dimensions of Industry 4.0. remain less systematically connected than productivity or innovation indicators. On that basis, this paper examines safety and training jointly as complementary dimensions of the working environment to provide a more comprehensive interpretation of industrial transformation.

Methodology.

A descriptive and comparative approach is used to examine occupational safety and training as two key dimensions of the working environment in the context of Industry 4.0. The analysis focuses on the European Union, Germany, Spain and Romania, selected because they reflect different industrial structures, technological trajectories and labor market conditions within Europe. The empirical analysis relies on harmonized Eurostat statistics and distinguishes between total economic activity and manufacturing to capture differences by sector associated with industrial transformation.

The occupational safety dimension uses Eurostat data on non-fatal accidents at work from 2015 to 2023. The analysis considers accident incidence and the severity structure of accidents involving at least four days of absence. Fatal accidents fall outside the empirical scope of the paper. In addition to levels and trends, the study uses derived indicators including cumulative changes, annual rates of variation, averages before and after the pandemic, relative manufacturing differentials and changes in severity composition. Severity is examined through the share of accidents involving at least 21 days of absence, at least one month of absence, and permanent incapacity or at least 183 days of absence. A lost days per case index is also calculated using fixed interval weights. This index is not intended to provide an exact medical measure of injury burden. It offers a consistent comparative approximation of the temporal load associated with accidents.

The training dimension combines two Eurostat sources. The first source measures participation in education and training among employed adults aged 18 to 64 from 2015 to 2024. The second source measures the proportion of enterprises providing continuing vocational training or other training related to the job to their employees in the available survey waves for 2010, 2015, and 2020. For both dimensions, the analysis combines direct indicators with derived comparative measures, including period averages, gaps with respect to the European Union benchmark, and manufacturing differentials.

The methodology rests on three decisions. It uses harmonized official statistics, combines direct and derived indicators, and treats occupational safety and training as complementary dimensions of the working environment. No causal relationship between digitalization and labor outcomes is claimed. The aim is to identify consistent comparative patterns that help to interpret the quality and sustainability of Industry 4.0. trajectories across national and sectoral settings.

Results and discussions.

Safety trends in total activity and manufacturing.

The empirical analysis begins with non-fatal accident incidence, which provides the clearest initial view of how occupational safety evolved in total economic activity and

manufacturing. Figure 1 shows the incidence rate for the European Union, Germany, Spain and Romania between 2015 and 2023. The Romanian series is represented on a secondary axis because its level is markedly lower than that of the other cases.

The figure shows a general downward trajectory in all four cases, although with differences in level and sectoral intensity. In total economic activity, the European Union, Germany, and Spain record declining incidence, while Romania remains at markedly lower levels throughout the period. In manufacturing, incidence also falls, but the sector remains systematically more exposed than the overall economy. Spain displays the highest manufacturing incidence in the comparison, Germany follows a more contained downward path, and Romania remains on a separate, lower incidence scale. Overall, Figure 1 shows improvement in accident incidence, but not the disappearance of the manufacturing safety gap.

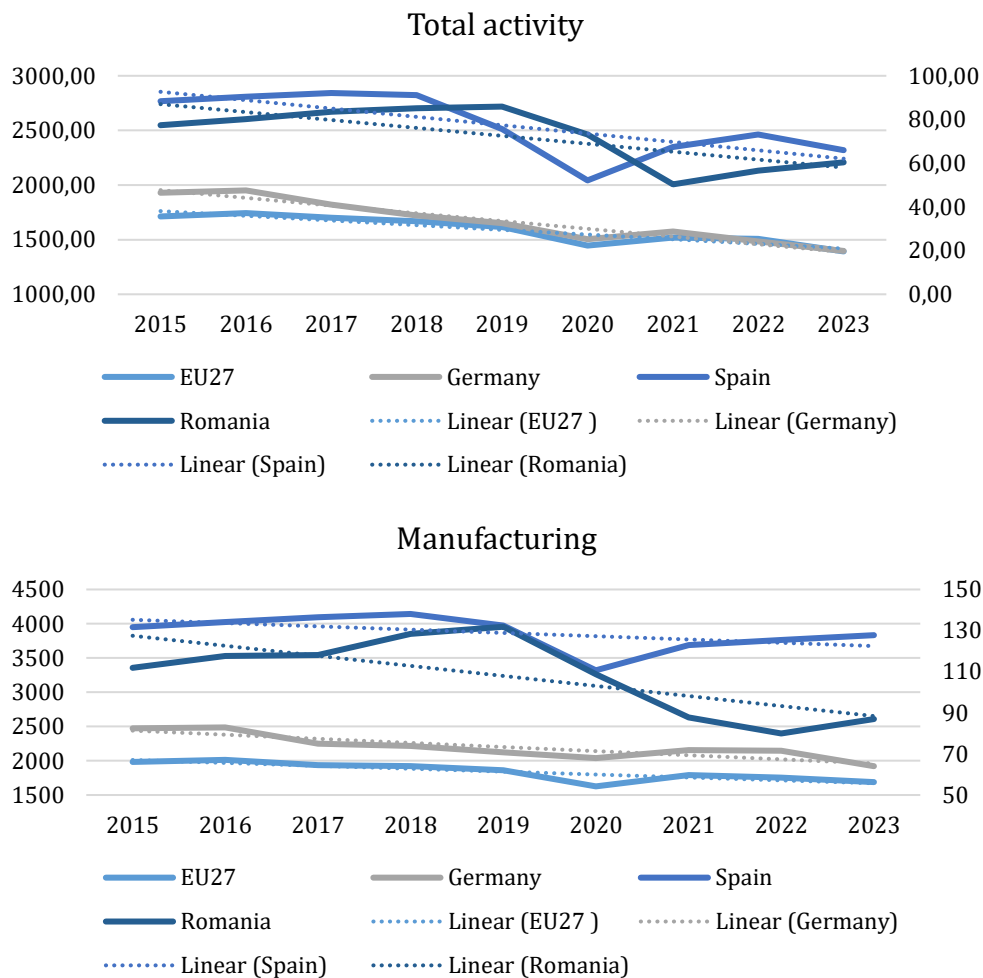


Figure 1. Non-fatal accident incidence rate in total economic activity and manufacturing. EU(27), Germany, Spain and Romania, 2015-2023.

(Source: Authors' own elaboration based on Eurostat>Home>Database>Cross cutting topics>Quality of employment>Safety and ethics of employmen).

Table 1 complements Figure 1 by summarizing cumulative changes, relative changes and annual rates of variation before and after 2019. It confirms the general reduction in accident incidence but also shows that the pace of improvement differs across countries and sectors. In total economic activity, the European Union, Germany and Spain record substantial absolute declines, while Romania shows a smaller absolute change because it starts from a much lower incidence base. In manufacturing, the contrast is stronger. The decline is clear in the European Union, Germany and Romania, whereas Spain records only a limited reduction over the whole period. The table therefore shows that incidence falls

overall, but that the improvement is uneven and particularly weak in Spanish manufacturing.

Table 1. Metrics of non-fatal accident incidence: cumulative change and rates of variation in total economic activity and manufacturing. EU(27), Germany, Spain and Romania, 2015-2023.

Total economic activity	Absolute change 15-23	Relative change 15-23	CAGR 15-19	CAGR 19-23
EU(27)	-319.00	-0.19	-0.01	-0.04
Germany	-533.77	-0.28	-0.04	-0.04
Spain	-447.26	-0.16	-0.02	-0.02
Romania	-17.03	-0.22	0.03	-0.08
Manufacturing	Absolute change 15-23	Relative change 15-23	CAGR 15-19	CAGR 19-23
EU(27)	-295.77	-0.15	-0.02	-0.02
Germany	-552.88	-0.22	-0.04	-0.02
Spain	-116.28	-0.03	0.00	-0.01
Romania	-24.84	-0.22	0.04	-0.10

(Source: Authors' own elaboration based on Eurostat>Home>Database>Cross cutting topics>Quality of employment>Safety and ethics of employment)

Table 2 compares average incidence before and after the pandemic and the relative position of each country with respect to the European benchmark. This distinction is relevant because a lower incidence level over time does not necessarily mean convergence toward the European average. The comparison shows that average incidence declines between the period before the pandemic and the period after the pandemic in all four cases. However, absolute improvement does not always imply convergence toward the European benchmark. Germany moves close to the EU average in total economic activity, while Spain remains clearly above it and even worsens its relative position by 2023. In manufacturing, the sectoral contrast is stronger: Spain continues to show the largest relative gap, Germany remains moderately above the EU average, and Romania stays well below it. This confirms that the Spanish manufacturing case combines improvement over time with persistent relative overexposure.

Table 2. Non-fatal accident incidence: averages for 2017-2019 and 2021-2023, post-pre difference and relative position. EU(27), Germany, Spain and Romania.

Total economic activity	Pre-average (17-19)	Post-average (21-23)	Post-pre difference	Relative position vs EU(27)	
				2019	2023
EU(27)	1662.35	1472.84	-189.51	0.00	0.00
Germany	1730.63	1484.73	-245.90	0.02	0.00
Spain	2726.52	2377.15	-349.37	0.56	0.67
Romania	84.90	55.74	-29.16	-0.95	-0.96
Manufacturing	Pre-average (17-19)	Post-average (21-23)	Post-pre difference	Relative position vs EU(27)	
				2019	2023
EU(27)	1906.03	1744.01	-162.02	0.00	0.00
Germany	2194.54	2073.72	-120.82	0.14	0.14
Spain	4071.03	3762.05	-308.97	1.14	1.27
Romania	126.13	84.89	-41.24	-0.93	-0.95

(Source: Authors' own elaboration based on Eurostat>Home>Database>Cross cutting topics>Quality of employment>Safety and ethics of employment)

Table 3 examines whether manufacturing remains more exposed than total economic activity within each country. It uses the ratio between manufacturing incidence and total incidence, together with the excess relative to the European benchmark. The results confirm that manufacturing remains more exposed to accidents than total economic activity in all cases, with ratios above one in both 2019 and 2023. The differential widens in the European Union, Germany and Spain, while it declines in Romania. Spain records the highest manufacturing differential in both years, rising from 1.58 to 1.65, which confirms the persistence of sectoral overexposure. Romania reduces its differential, although manufacturing remains more exposed than the national economy. The table therefore reinforces one of the central findings of the safety analysis: lower incidence has not eliminated the structural risk differential of manufacturing.

Table 3. Manufacturing incidence differential relative to total economic activity, 2019 and 2023. Excess relative to EU(27) in percentage points.

	Ratio 2019 (manuf./total)	Ratio 2023 (manuf./total)	Differential % 2019	Differential % 2023	Change 19-23 (p.p.)	Excess vs EU(27), 19	Excess vs EU(27), 23
EU(27)	1.15	1.21	15.17%	21.14%	0.06		
Germany	1.28	1.38	28.49%	37.51%	0.09	0.13	0.16
Spain	1.58	1.65	58.18%	65.16%	0.07	0.43	0.44
Romania	1.53	1.44	53.47%	44.21%	-0.09	0.38	0.23

(Source: Authors' own elaboration based on Eurostat>Home>Database>Cross cutting topics>Quality of employment>Safety and ethics of employment)

Overall, the incidence of non-fatal accidents evolves favorably, but not uniformly. Incidence declines in total economic activity and manufacturing, yet manufacturing remains structurally more exposed in all cases. Germany combines decline with relative convergence, Spain combines absolute improvement with persistent manufacturing gaps, and Romania improves from a markedly lower incidence base while reducing its sectoral differential. The safety dimension therefore requires attention not only to average decline, but also to sectoral distribution and comparative position.

Severity and quality of safety improvement.

The previous subsection showed that non-fatal accident incidence generally declined. However, lower frequency does not necessarily imply an equivalent improvement in the quality of occupational safety. A decline in accidents may coexist with a less favorable severity profile if the remaining cases become longer or more demanding. For this reason, the analysis now moves from incidence to severity.

Table 4 examines the severity composition of accidents involving at least four days of absence. It considers three thresholds, accidents involving at least 21 days of absence, at least one month of absence, and permanent incapacity or at least 183 days of absence. The results indicate a shift toward longer durations in part of the comparison. Germany shows the most contained profile. The European Union records moderate increases. Spain remains above the European average and deteriorates slightly. Romania records the highest shares and the sharpest worsening, especially in long duration cases. These results show that a decline in incidence does not necessarily lead to an equivalent improvement in severity.

Table 4. Severity composition of accidents with at least four lost days. Total economic activity and manufacturing. EU(27), Germany, Spain and Romania, 2019 and 2023.

Total economic activity	Long duration share 2019 (≥ 21 days)	Share ≥ 1 month 2019	Share 183 days+ 2019	Long-duration share 2023 (≥ 21 days)	Share ≥ 1 month 2023	Share 183 days+ 2023
EU(27)	0.33	0.23	0.04	0.34	0.24	0.05
Germany	0.22	0.15	0.02	0.22	0.16	0.02
Spain	0.37	0.25	0.03	0.39	0.27	0.04
Romania	0.43	0.32	0.04	0.54	0.40	0.05
Manufacturing	Long duration share 2019 (≥ 21 days)	Share ≥ 1 month 2019	Share 183 days+ 2019	Long-duration share 2023 (≥ 21 days)	Share ≥ 1 month 2023	Share 183 days+ 2023
EU(27)	0.30	0.20	0.03	0.30	0.21	0.04
Germany	0.18	0.12	0.02	0.17	0.12	0.02
Spain	0.36	0.24	0.03	0.37	0.25	0.03
Romania	0.48	0.37	0.04	0.59	0.44	0.05

(Source: Authors' own elaboration based on Eurostat>Home>Database>Cross cutting topics>Quality of employment>Safety and ethics of employment)

Table 5 reports changes in severity composition from 2019 to 2023. It shows whether longer absence categories gained weight within accidents involving at least four days of absence and whether this change was similar across countries and sectors. The results confirm that the change in severity composition is uneven. Germany remains broadly stable, while the European Union records moderate increases. Spain shows a clearer deterioration, especially in long-duration cases and absences of at least one month. Romania displays by far the strongest worsening in both total economic activity and manufacturing. The table therefore reinforces the previous result by showing that the qualitative structure of safety improvement differs substantially across countries.

Table 5. Changes in accident severity composition, 2019-2023. Total economic activity and manufacturing. EU(27), Germany, Spain and Romania, percentage points.

Total economic activity	Δ Long duration cases	$\Delta \geq 1$ month	Δ 183 days +
EU(27)	0.94	1.11	0.68
Germany	-0.14	0.15	0.04
Spain	1.57	1.70	0.52
Romania	10.74	8.67	0.92
Manufacturing	Δ Long duration cases	$\Delta \geq 1$ month	Δ 183 days +
EU(27)	0.58	0.77	0.60
Germany	-0.30	0.06	0.31
Spain	1.54	1.63	0.57
Romania	10.72	6.97	0.79

(Source: Authors' own elaboration based on Eurostat>Home>Database>Cross cutting topics>Quality of employment>Safety and ethics of employment)

Table 6 summarizes the severity burden through a lost days per case index based on fixed interval weights. The index does not provide an exact medical measure of injury duration, but it gives a consistent comparative approximation of the temporal load associated with accidents. The same pattern appears in Table 6. The index rises in the European Union, Spain and Romania, while Germany remains almost unchanged. Romania records both the highest values and the strongest increase in total economic activity and manufacturing. This confirms that, even where accident incidence falls, the average duration associated with accidents may become heavier. The result is important because it connects accident severity with its organizational burden.

Table 6. Lost days per case index. Total economic activity and manufacturing. EU(27), Germany, Spain and Romania, 2019 and 2023.

Total economic activity	2019	2023
EU(27)	29.84	31.18
Germany	22.84	22.92
Spain	29.52	30.96
Romania	34.12	39.70
Manufacturing	2019	2023
EU(27)	27.34	28.41
Germany	20.48	20.84
Spain	28.67	30.14
Romania	36.07	40.92

(Source: Authors' own elaboration based on Eurostat>Home>Database>Cross cutting topics>Quality of employment>Safety and ethics of employment.

Note: Average weights by duration interval = 12, 26, 60 and 183 days)

The severity evidence qualifies the favorable picture reflected by incidence trends. Accident frequency declines across the comparison, but severity does not follow the same path. Longer absences gain relative weight in the European Union, Spain, and Romania, and the lost days per case index also increases in those cases. Germany shows the most stable profile, Spain combines falling incidence with a less favorable severity pattern, and Romania records the sharpest deterioration despite maintaining low incidence levels. For this reason, the assessment of occupational safety must consider both frequency and severity.

Training dynamics and learning capacity.

Training is examined as the adaptive dimension of the working environment. It captures the capacity of workers and firms to update skills, absorb technological change and reorganize work in more digitalized production settings. The analysis therefore considers adult participation in education and training together with the training effort made by enterprises. Table 7 reports participation in education and training among employed adults between 2015 and 2024. Adult learning increases after 2020 in most cases, but the pattern is not uniform. The European Union records a gradual rise, Germany remains comparatively flat, and Spain and Romania show the strongest acceleration. In manufacturing, participation is generally lower at the beginning of the period, but Spain and Romania rise above the EU manufacturing average by 2024. This indicates that the strongest post-2020 intensification of adult learning is concentrated in Spain and Romania.

Table 7. Participation of the employed population in education and training. Total economic activity and manufacturing. EU(27), Germany, Spain and Romania, 2015-2024

Total economic activity									
2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
EU(27)									
13.70	13.80	13.90	14.10	14.30	12.30	14.40	15.70	16.70	17.40
Germany									
12.40	12.60	12.50	12.50	12.60	12.30	12.00	12.70	12.70	13.90
Spain									
12.00	11.30	11.90	12.60	12.50	13.00	17.30	18.40	18.80	19.00
Romania									
1.80	1.50	1.40	1.20	1.60	1.10	7.50	8.10	9.90	13.10
Manufacturing									
2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
EU(27)									
9.20	9.30	9.20	9.10	9.30	7.90	8.80	10.00	10.90	11.60
Germany									
9.50	9.40	8.20	9.20	9.10	9.40	8.10	8.60	8.70	9.60
Spain									
8.30	8.20	8.00	8.10	8.40	8.70	10.90	11.70	13.00	13.40
Romania									
1.40	1.40	1.10	0.80	2.20	1.60	6.70	7.40	9.60	13.20

(Source: Authors' own elaboration based on Eurostat> Home>Database>Population and social conditions>Education and training)

Tables 8 and 9 clarify whether the increase in adult learning reflects a temporary fluctuation or a more persistent shift. The comparison between 2017-2019 and 2021-2023 shows moderate improvement in the European Union, almost no progress in Germany and strong increases in Spain and Romania. The gap with respect to the EU benchmark confirms this divergence. Germany moves further below the European average by 2024, while Spain moves above it in both total economic activity and manufacturing. Romania narrows its gap substantially in total economic activity and surpasses the EU manufacturing average by 2024. Adult learning therefore shows convergence in Spain and Romania, but not in Germany.

Table 8. Pre- and post-period averages for adult learning participation among the employed population. Total economic activity and manufacturing. EU(27), Germany, Spain and Romania, 2017-2019 and 2021-2023.

Total economic activity	Average 17-19	Average 21-23	Post-pre difference
EU(27)	14.10	15.60	1.50
Germany	12.53	12.47	-0.07
Spain	12.33	18.17	5.83
Romania	1.40	8.50	7.10
Manufacturing	Average 17-19	Average 21-23	Post-pre difference
EU(27)	9.20	9.90	0.70
Germany	8.83	8.47	-0.37
Spain	8.17	11.87	3.70
Romania	1.37	7.90	6.53

(Source: Authors' own elaboration based on Eurostat> Home>Database>Population and social conditions>Education and training)

Table 9. Gap in adult learning participation relative to the EU. Total economic activity and manufacturing. EU(27), Germany, Spain and Romania, 2019 and 2024.

Total economic activity	Gap 2019	Gap 2024
EU(27)	0.00	0.00
Germany	-1.70	-3.50
Spain	-1.80	1.60
Romania	-12.70	-4.30
Manufacturing	Gap 2019	Gap 2024
EU(27)	0.00	0.00
Germany	-0.20	-2.00
Spain	-0.90	1.80
Romania	-7.10	1.60

(Source: Authors' own elaboration based on Eurostat> Home>Database>Population and social conditions>Education and training)

Participation by workers does not exhaust the training dimension. Tables 10 and 11 shift the focus to enterprises providing continuing vocational training. This indicator captures the organizational commitment of firms to workforce development. The results show a polarized pattern. Germany and Spain remain above the EU average in both total economic activity and manufacturing, although Spain's advantage narrows by 2020. Romania remains far below the European benchmark in all years and sectors. This contrast is important because it shows that a marked increase in adult learning does not automatically imply a comparable commitment by firms to provide training.

Table 10. Enterprises that provide continuing vocational training to their employees in total economic activity and manufacturing. EU(27), Germany, Spain, and Romania, 2010, 2015, and 2020.

Total economic activity	Year		
	2010	2015	2020
EU(27)	63.60	70.50	67.40
Germany	72.80	77.30	77.20
Spain	74.90	86.00	73.20
Romania	24.10	26.70	17.50
Manufacturing	Year		
	2010	2015	2020
EU(27)	60.90	69.50	70.50
Germany	72.80	79.90	78.20
Spain	74.30	87.20	74.00
Romania	24.40	27.30	21.70

(Source: Authors' own elaboration based on Eurostat> Home>Database>Population and social conditions>Education and training)

Table 11. Gap relative to the EU in enterprises providing continuing vocational training. Total economic activity and manufacturing. EU(27), Germany, Spain and Romania, 2010, 2015 and 2020.

Total economic activity	Gap 2010	Gap 2015	Gap 2020
EU(27)	0.00	0.00	0.00
Germany	9.20	6.80	9.80
Spain	11.30	15.50	5.80
Romania	-39.50	-43.80	-49.90
Manufacturing	Gap 2010	Gap 2015	Gap 2020
EU(27)	0.00	0.00	0.00
Germany	11.90	10.40	7.70
Spain	13.40	17.70	3.50
Romania	-36.50	-42.20	-48.80

(Source: Authors' own elaboration based on Eurostat> Home>Database>Population and social conditions>Education and training)

A final issue concerns the relative position of manufacturing within each country. Table 12 examines whether manufacturing is more or less intensive in training than the overall economy. The pattern is mixed but informative. In the European Union, manufacturing moves from a negative differential to a positive one by 2020. Germany and Spain also show positive differentials after 2010, while Romania records the strongest positive differential in 2020. This does not mean that Romanian firms provide high levels of training in absolute terms. Instead, it indicates that, within Romania, manufacturing is relatively more engaged in training provision than the rest of the economy.

Table 12. Industrial differential in enterprise training provision, manufacturing relative to total economic activity. EU(27), Germany, Spain and Romania, 2010, 2015 and 2020.

	2010	2015	2020
EU(27)	-2.70	-1.00	3.10
Germany	0.00	2.60	1.00
Spain	-0.60	1.20	0.80
Romania	0.30	0.60	4.20

(Source: Authors' own elaboration based on Eurostat> Home>Database>Population and social conditions>Education and training)

The training evidence points to differentiated trajectories. Adult learning expands strongly in Spain and Romania after 2020, while Germany loses relative ground. Training provided by enterprises follows another pattern. Germany and Spain remain above the European benchmark, whereas Romania stays far below it. The training dimension therefore cannot be assessed using a single indicator because individual participation and firms' own training effort do not move in the same way.

Comparative interpretation of national trajectories.

The results do not point to a single pattern linking digital transformation and the working environment. They reveal three distinct national trajectories, each combining safety and training differently. Reading these dimensions together matters because the quality of the transition toward Industry 4.0. depends not only on whether accident incidence falls or training expands, but also on how both processes interact within each national and sectoral context.

These trajectories also connect with previous research on Industry 4.0., occupational safety, training, and knowledge management. The literature recognizes that digital technologies may improve monitoring, process control, and safety management, but it also warns that new occupational safety and health challenges arise when technological change is not accompanied by prevention systems, work organization, and human

adaptation (Badri et al., 2018; Rosen, 2022; Forcina et al., 2021; Arana-Landín et al., 2023). The evidence presented here is consistent with this more nuanced interpretation. Accident incidence declines, but severity worsens in the European Union, Spain, and Romania. Adult learning expands in Spain and Romania, but training provided by enterprises remains much more uneven. From a knowledge management perspective, this confirms that the quality of Industry 4.0. depends not only on technological diffusion, but also on the capacity to transfer preventive knowledge, update skills, and embed learning within firms.

Germany presents the most stable profile in the comparison. In safety, it combines declining accident incidence, relative convergence toward the European benchmark and limited deterioration in severity indicators. Manufacturing remains more exposed than the total economy, but the overall pattern is comparatively contained. The training dimension is more mixed. Adult learning does not accelerate as strongly as in Spain or Romania, and Germany moves further below the European average by 2024. However, firms remain strongly engaged in continuing vocational training. The German case therefore reflects a trajectory based less on rapid expansion than on institutional stability, organizational continuity, and a comparatively controlled safety profile.

Spain's case follows a more ambivalent path. Accident incidence declines in both total economic activity and manufacturing, but manufacturing continues to record the highest incidence levels and the widest differential relative to the total economy. The severity indicators reinforce this weaker position, because falling incidence coexists with a less favorable internal structure of accidents. Training evolves more positively. Spain records a strong increase in adult learning and moves above the European benchmark in both total economic activity and manufacturing. Training provided by enterprises also remains above the European average, although the gap narrows by 2020. The Spanish case therefore combines a strengthening of adaptive capacity with persistent safety weaknesses in manufacturing.

Romania presents the most dynamic and fragile national profile. Accident incidence remains far below the other cases throughout the comparison, but this favorable position is qualified by a sharper deterioration in severity indicators. Adult learning expands strongly after 2020. Romania narrows its gap with the European benchmark in total economic activity and moves above the European manufacturing average by 2024. However, this convergence is not reproduced in training provided by enterprises, where Romanian firms remain far below the European pattern. The Romanian case therefore combines rapid progress in individual learning participation with persistent weaknesses in firm training and accident severity.

Viewed together, these trajectories show that the relationship between Industry 4.0. and the working environment is neither automatic nor uniform. Germany illustrates a more stable and institutionally grounded path. Spain reflects a mixed trajectory in which stronger training capacity coexists with persistent safety gaps. Romania shows a rapid but uneven process of convergence. What matters, then, is not only whether technology spreads, but whether safer production conditions and training mechanisms capable of sustaining adaptation over time accompany that process. Seen in this way, the working environment does not merely reflect industrial transformation. It also helps to shape its quality and durability.

Conclusions.

Improving the working environment belongs to the substance of Industry 4.0. rather than to its margins. The comparative evidence for the European Union, Germany, Spain, and Romania shows that industrial transformation cannot be reduced to gains in efficiency, productivity, or technological upgrading alone. Its quality is also shaped by the conditions under which work is organized, protected, and renewed. Occupational safety and training therefore form part of the core architecture of digital industrial change.

The results confirm a general decline in non-fatal accident incidence in both total economic activity and manufacturing. That pattern is consistent with an overall strengthening of occupational safety. However, this interpretation requires further qualification. Lower accident frequency does not systematically coincide with a more favorable severity profile. In several cases, longer absences gain relative weight and the burden reflected in lost days per case increases. The same unevenness appears in the training dimension. Participation in adult learning expands strongly in part of the sample, especially after 2020, whereas training provided by enterprises remains much more dependent on the structure and capacity of each national system. The working environment therefore evolves in differentiated ways rather than along a single, uniform path.

The comparison across countries reinforces this point. Germany shows the most robust profile in the sample. It combines declining incidence, limited deterioration in severity and a strong base of continuing vocational training in firms. Spain records substantial progress, especially in adult learning, which marks an important strengthening of adaptive capacity. At the same time, Spanish manufacturing continues to display persistent weaknesses in its safety profile, with less favorable results in both incidence and severity. Romania presents the fastest expansion in adult learning participation and maintains low accident incidence levels, yet that more favorable picture is qualified by a sharper worsening in severity indicators and by a much weaker enterprise training base. These trajectories do not represent different speeds of a single transition. They reflect different configurations of industrial change, each with its own balance between protection, adaptation, and organizational support.

The main contribution of the paper lies in reading occupational safety and training together within one comparative framework. By combining accident incidence, severity and training indicators, the paper shows that the quality of Industry 4.0. cannot be assessed only through technological upgrading, productivity or general labor market change. It also depends on whether safety improvement is sustained in qualitative terms and whether learning is embedded within firms. This joint approach offers a more complete assessment of the internal quality of digital industrial transformation.

The working environment can therefore be understood as a practical test of the quality of digital transformation. A transition may appear favorable when accident incidence falls or adult learning expands, but that assessment remains incomplete if accident severity increases or if training is not embedded within firms. Industry 4.0. should therefore be assessed not only by the spread of digital technologies, but also by the extent to which those technologies are absorbed into safer and more adaptive work systems. The quality of industrial transformation depends on this alignment between technological change, preventive capacity and organizational learning.

Given its descriptive and comparative design, the study does not estimate causal effects between digitalization and labor outcomes. Its contribution lies in clarifying how the working environment evolves alongside industrial transformation across countries and sectors. Within that scope, the evidence supports a central conclusion: occupational safety and training warrant a central place in the assessment of digital industrial change, not only as social concerns, but as conditions of resilience, balance and sustainable industrial development.

Credit Author Statement.

Sonia García-Moreno: Conceptualization, Methodology, Formal Analysis, Investigation, Data Curation, Writing - Original Draft, Visualization.

Víctor-Raúl López-Ruiz: Validation, Supervision, Project Administration.

AI Declaration.

The authors declare that no AI tools were used in any part of this study, including data handling, analysis, interpretation, or conclusion writing.

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